

A two-habit ice cloud model for remote sensing applications and radiative forcing studies

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In the study of ice cloud optical properties with modeling capabilities, there are **two major sources of uncertainties**:

- Inaccuracy of light scattering computational models
- Simplifications of particle geometries

Outline

1. New computational capabilities for light scattering simulations
2. A two-habit model for ice clouds
3. Conclusions

T-matrix method

- This is an exact method
 - Expand the incident and scattered electric fields in terms of suitable vector spherical wave functions
 - Relate the respective expansion coefficients by means of a transition matrix (or T matrix).
- After the T-matrix is known, it is straightforward to compute the scattering and absorption properties.

Field Expansion & T-matrix

Vector spherical functions

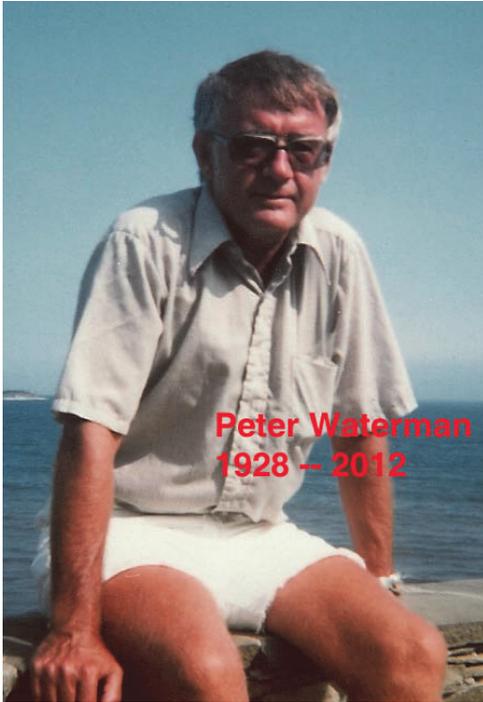
$$\vec{E}^{inc}(\vec{r}) = \sum_{n=1}^{\infty} \sum_{m=-n}^n a_{mn} Rg\vec{M}_{mn}(\vec{r}) + b_{mn} Rg\vec{N}_{mn}(\vec{r}) \quad \vec{r} \in V_{in}$$

$$\vec{E}^{sca}(\vec{r}) = \sum_{n=1}^{\infty} \sum_{m=-n}^n p_{mn} \vec{M}_{mn}(\vec{r}) + q_{mn} \vec{N}_{mn}(\vec{r}) \quad \vec{r} \in V_{out}$$

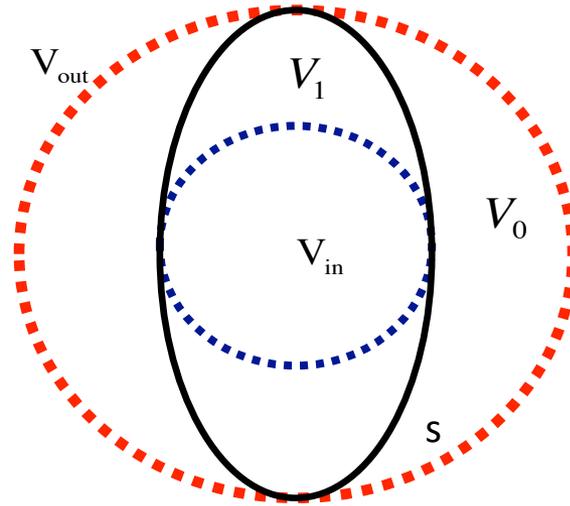
$$\begin{bmatrix} p_1 \\ q_1 \\ \dots \\ \dots \\ p_{l_{max}} \\ q_{l_{max}} \end{bmatrix} = \begin{bmatrix} T_{11}^{11} & T_{11}^{12} & \dots & \dots & T_{1,1_{max}}^{11} & T_{1,1_{max}}^{12} \\ T_{11}^{21} & T_{11}^{22} & \dots & \dots & T_{1,1_{max}}^{21} & T_{1,1_{max}}^{22} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ T_{l_{max},1}^{11} & T_{l_{max},1}^{12} & \dots & \dots & T_{l_{max},1_{max}}^{11} & T_{l_{max},1_{max}}^{12} \\ T_{l_{max},1}^{21} & T_{l_{max},1}^{22} & \dots & \dots & T_{l_{max},1_{max}}^{21} & T_{l_{max},1_{max}}^{22} \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ \dots \\ \dots \\ a_{l_{max}} \\ b_{l_{max}} \end{bmatrix}$$

T-matrix

Surface Integral Equation



$$T = -RgQ[Q]^{-1}$$



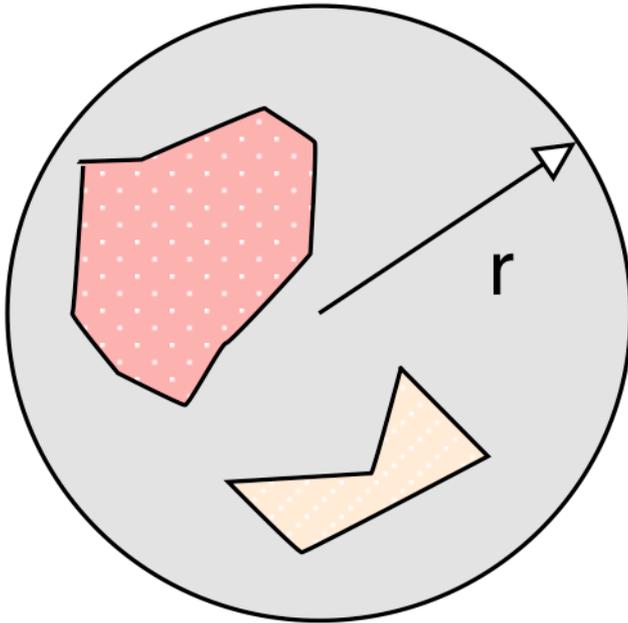
(Mishchenko and Martin, JQSRT, 123:2-7, 2013)

Extended boundary condition Method (EBCM)

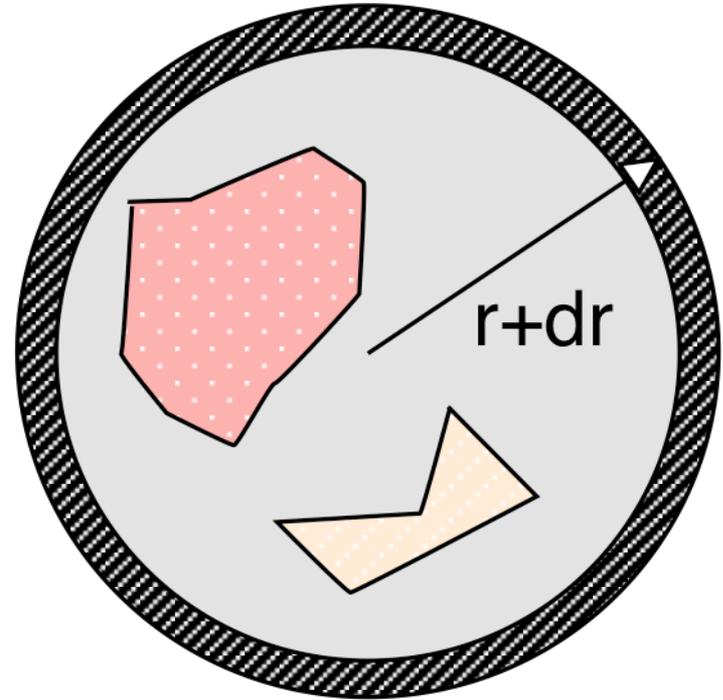
$$\vec{E}^{\text{inc}}(\vec{r}') = - \int_s ds \{ i\omega\mu_0 [\hat{n} \times \vec{H}(\vec{r})] \cdot \vec{G}(\vec{r}, \vec{r}') + [\hat{n} \times \vec{E}(\vec{r})] \cdot [\nabla \times \vec{G}(\vec{r}, \vec{r}')] \}, \quad \vec{r}' \in V_1$$

$$\vec{E}^{\text{sca}}(\vec{r}') = \int_s ds \{ i\omega\mu_0 [\hat{n} \times \vec{H}(\vec{r})] \cdot \vec{G}(\vec{r}, \vec{r}') + [\hat{n} \times \vec{E}(\vec{r})] \cdot [\nabla \times \vec{G}(\vec{r}, \vec{r}')] \}, \quad \vec{r}' \in V_0$$

Volume Integral Equation



(a)



(b)

$$\bar{E}(\bar{r}) = \bar{E}_{inc}(\bar{r}) + k^2 \int (m^2 - 1) \vec{G}(\bar{r} - \bar{r}') \cdot \bar{E}(\bar{r}') d^3 \bar{r}'$$

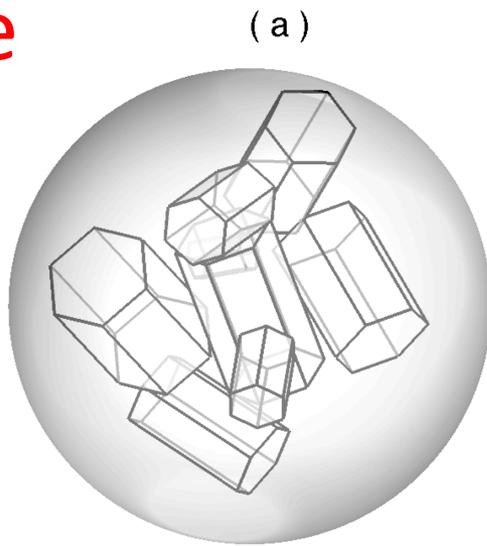
Invariant Imbedding

$$T_{mmn'}(r+dr) = Q_{11}^m(r+dr) + \left[\mathbf{I} + Q_{12}^m(r+dr) \right] \left[\mathbf{I} - T_{mmn'}(r) Q_{22}^m(r+dr) \right]^{-1} T_{mmn'}(r) \left[\mathbf{I} + \tilde{Q}_{12}^m(r+dr) \right]$$

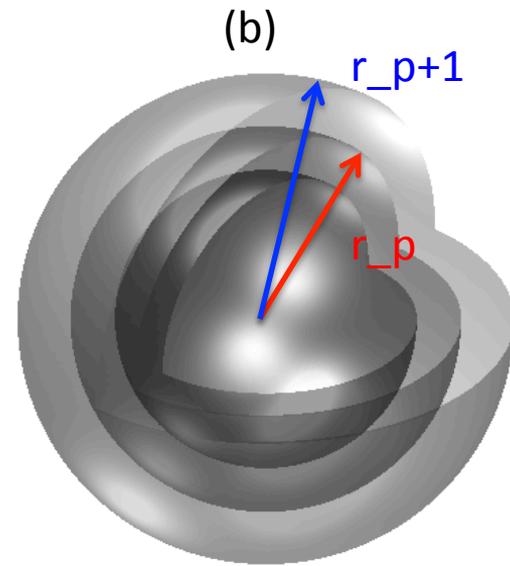
$$T_{mmn'}(r=0) = 0$$

Johnson (1988); Bi, Yang, Kattawar, and Mishchenko (2013) ⁶

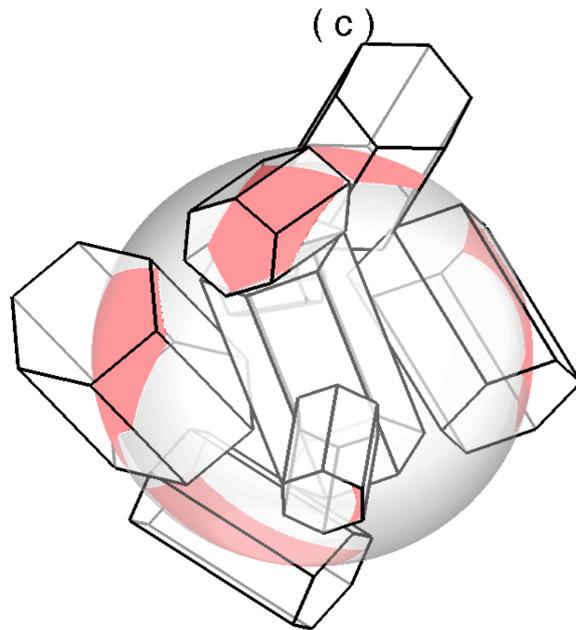
Example



An inhomogeneous sphere

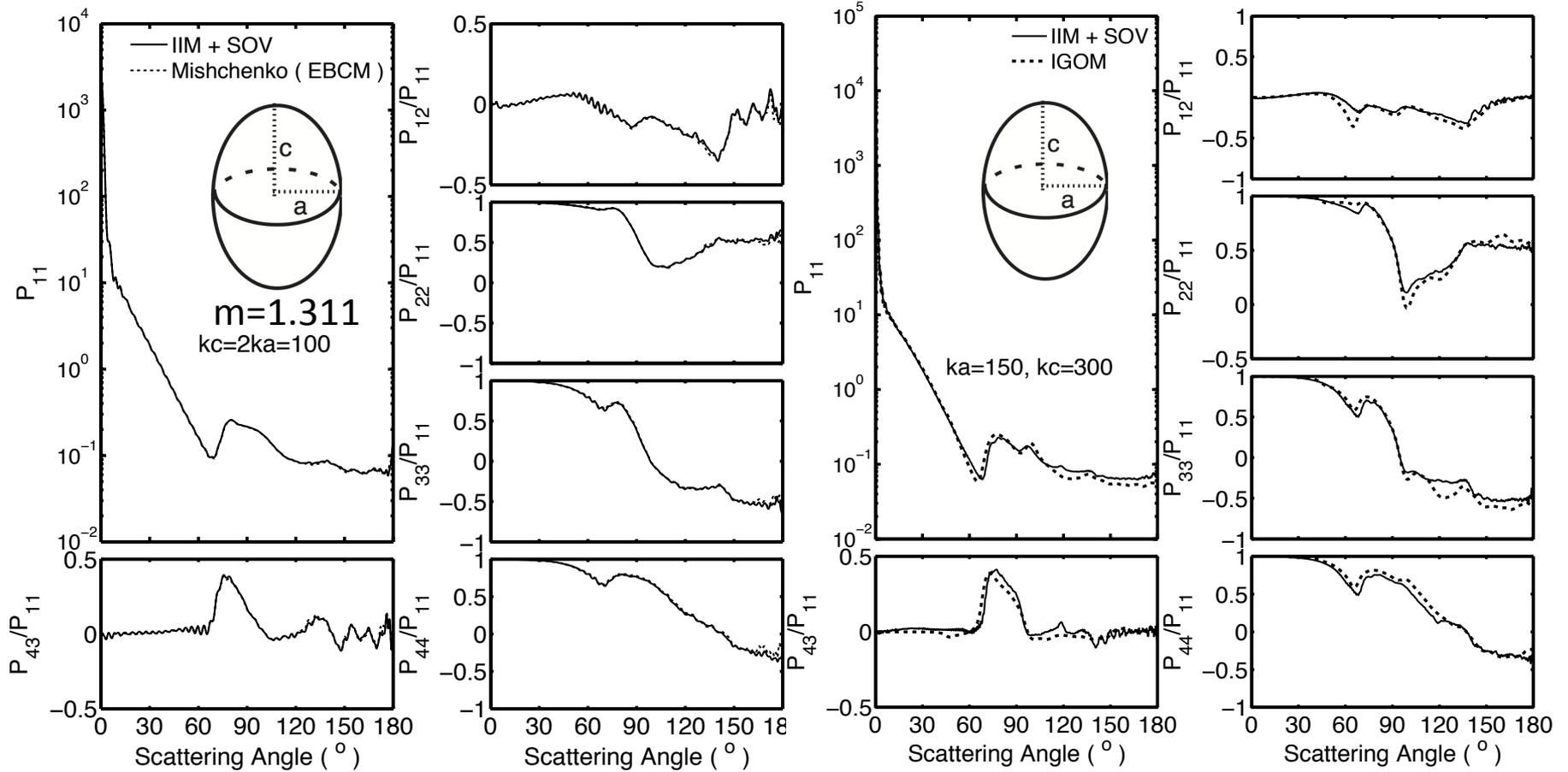


Discretize to multi-layered sphere

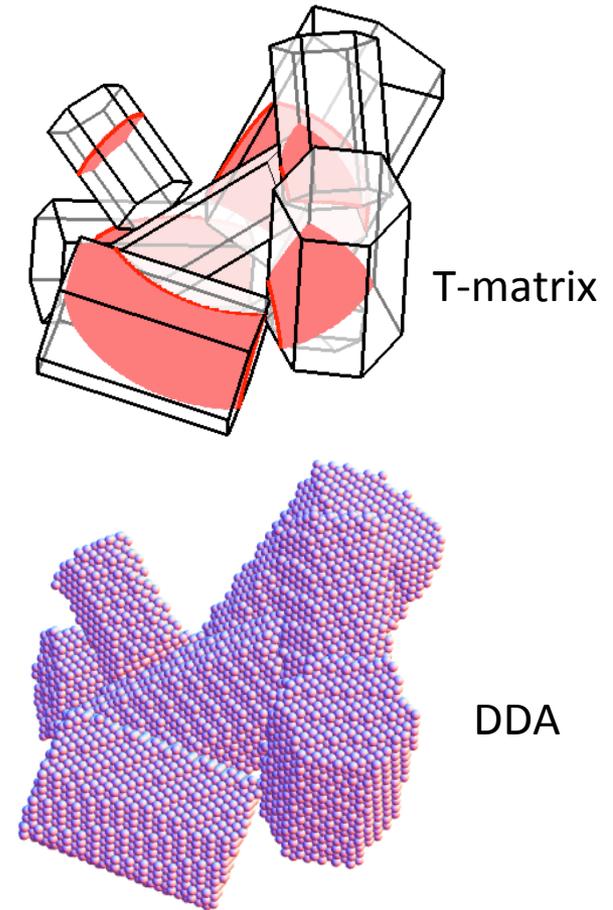
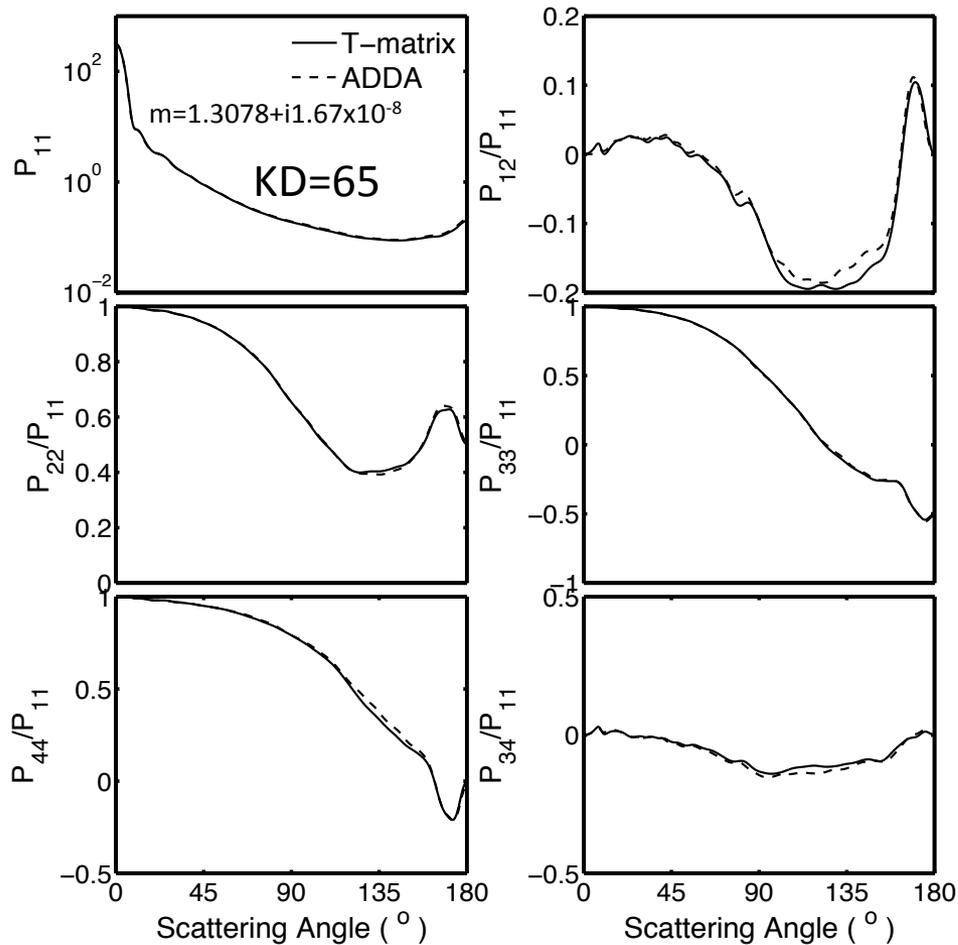


 Non-unity refractive index of each spherical surface

Validation of II-TM

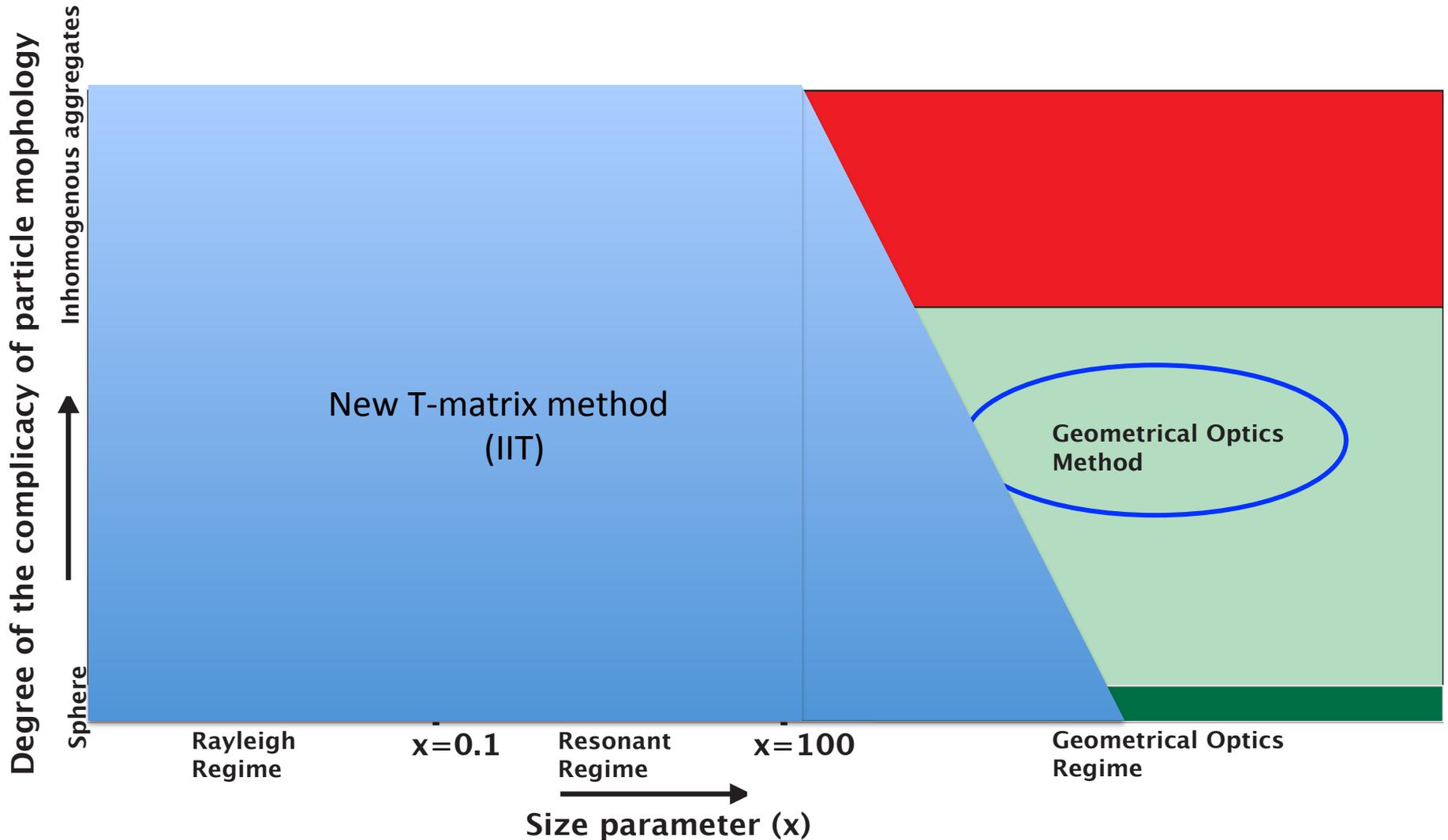


Comparison



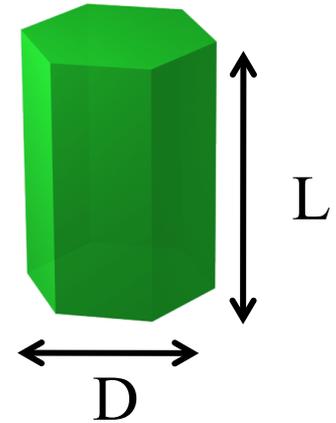
In the Discrete Dipole Approximation (DDA) simulation, 1056 orientations with 128 scattering planes are used to achieve the effect of random orientations.

Scattering Methods



The accuracy of the **conventional geometric optics method (CGOM)**

- **CGOM (Takano and Liou, 1989, Macke et al. 1996) has been widely used.**



- Scattering simulations in this study:

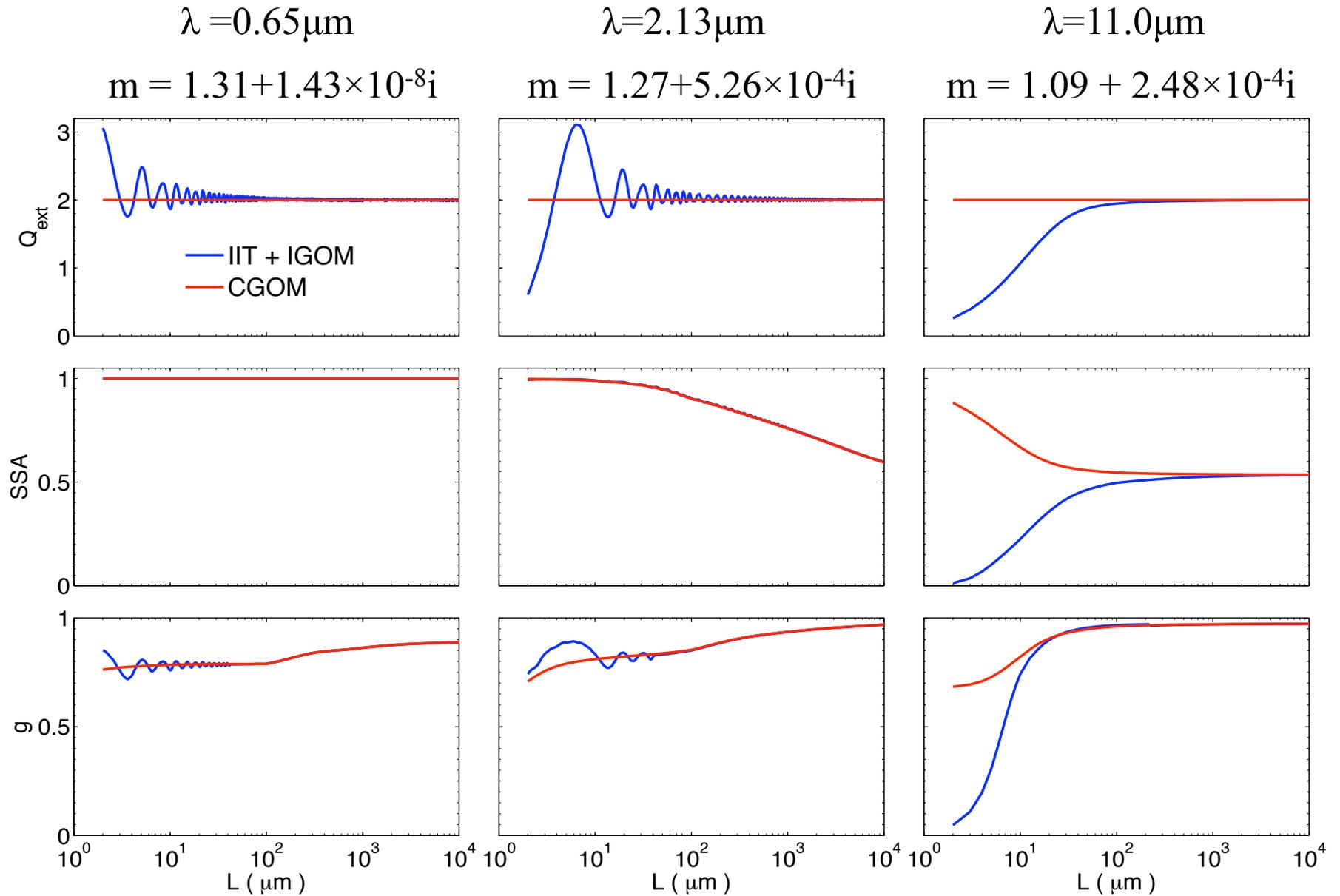
- **Accurate method: IIT + IGOM**

- **Approximate method: CGOM**

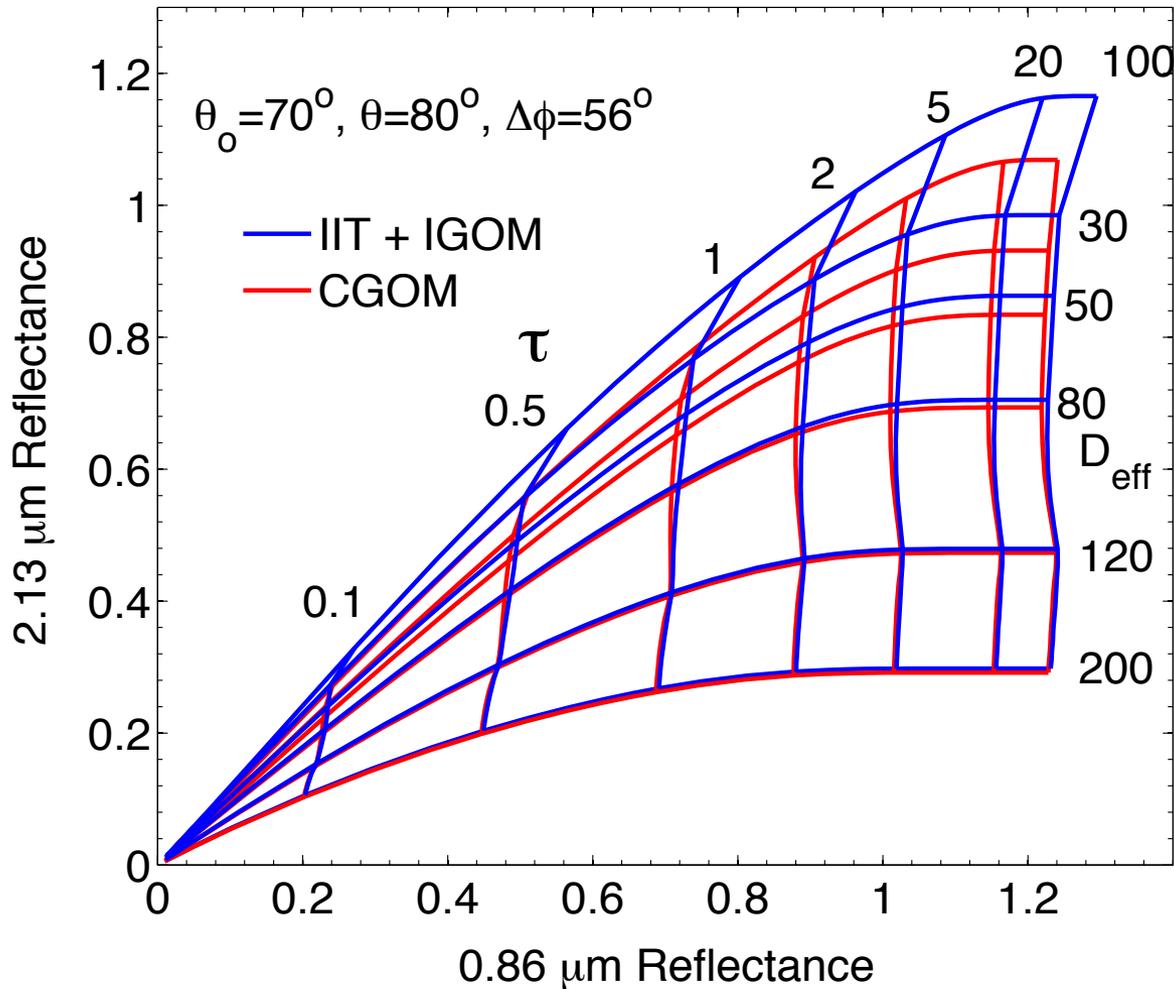
$$\frac{D}{L} = \begin{cases} 0.7 & L < 100 \mu m \\ 6.96/\sqrt{L} & L \geq 100 \mu m \end{cases}$$

- VIS/NIR and IR retrievals based on MODIS observations
- Radiative forcing: Single-column RTM and AGCM

IIT+IGOM vs CGOM: Single-scattering properties



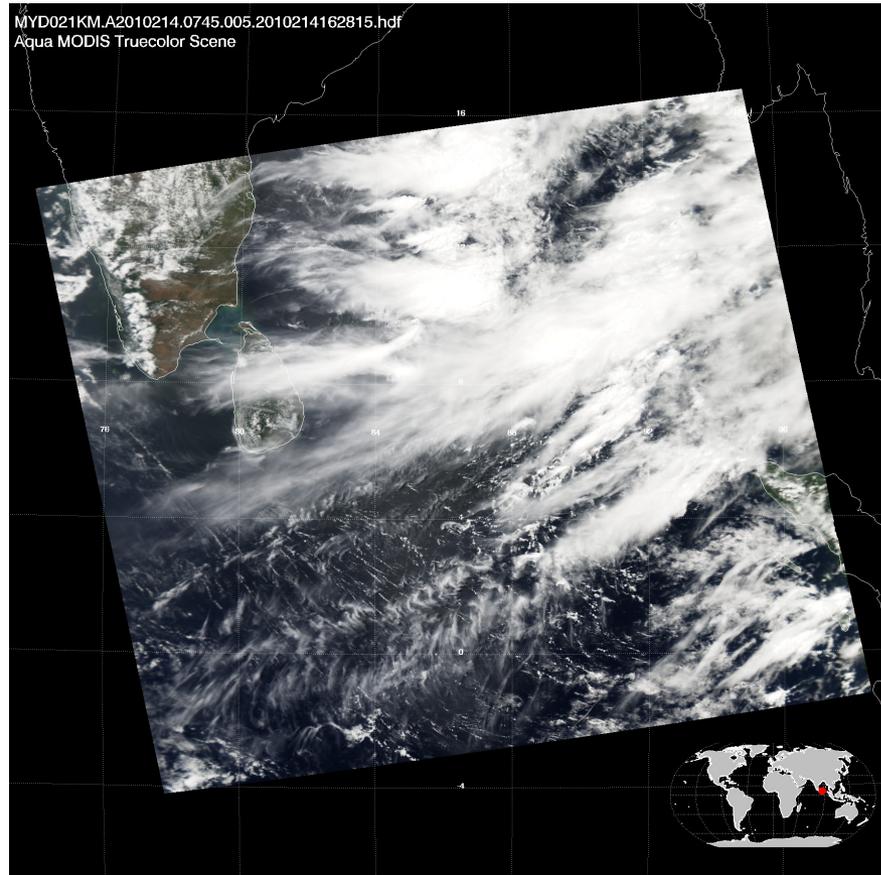
IIT + IGOM vs CGOM: VIS/NIR Retrieval



The scattering properties given by the IIT+IGOM and CGOM show effects on the reflectance of ice clouds with the effective particles size as large as 80 μm at VIS/NIR bands;

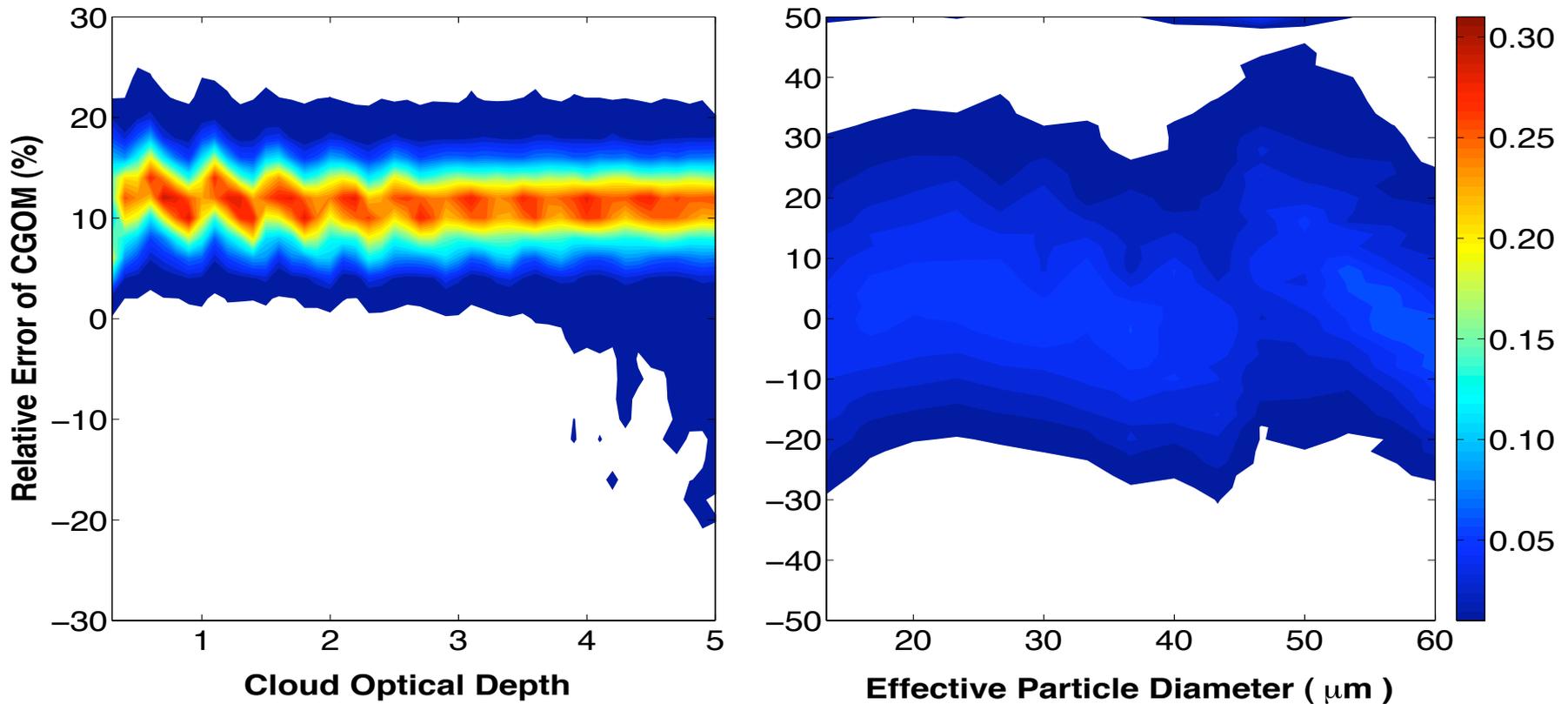
Reflectance functions based on the scattering properties from the IIT+IGOM and CGOM at the MODIS 0.86- and 2.13- μm bands.

MODIS Observations

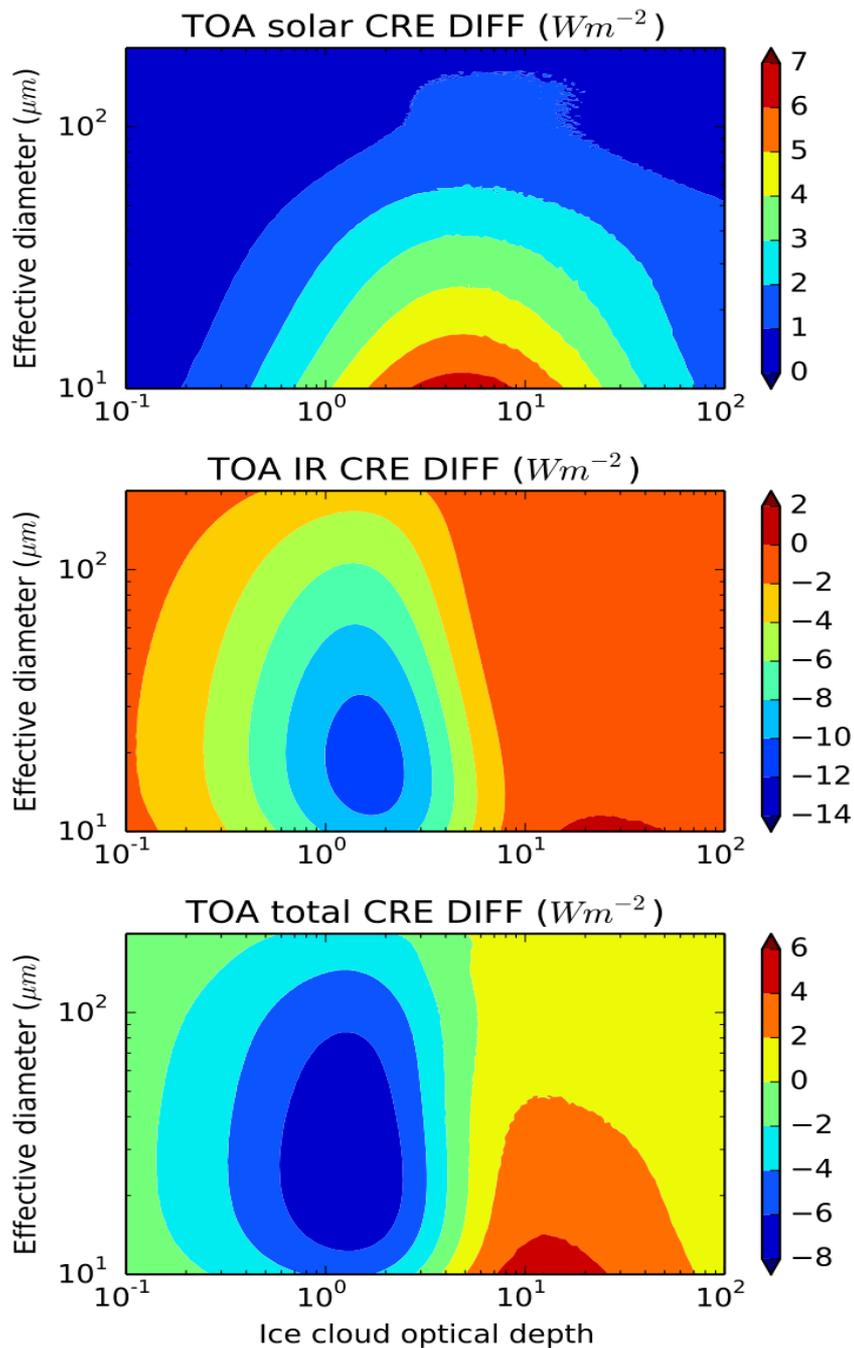


August 2, 2010, 07:45AM

IR Retrieval: relative errors of the CGOM



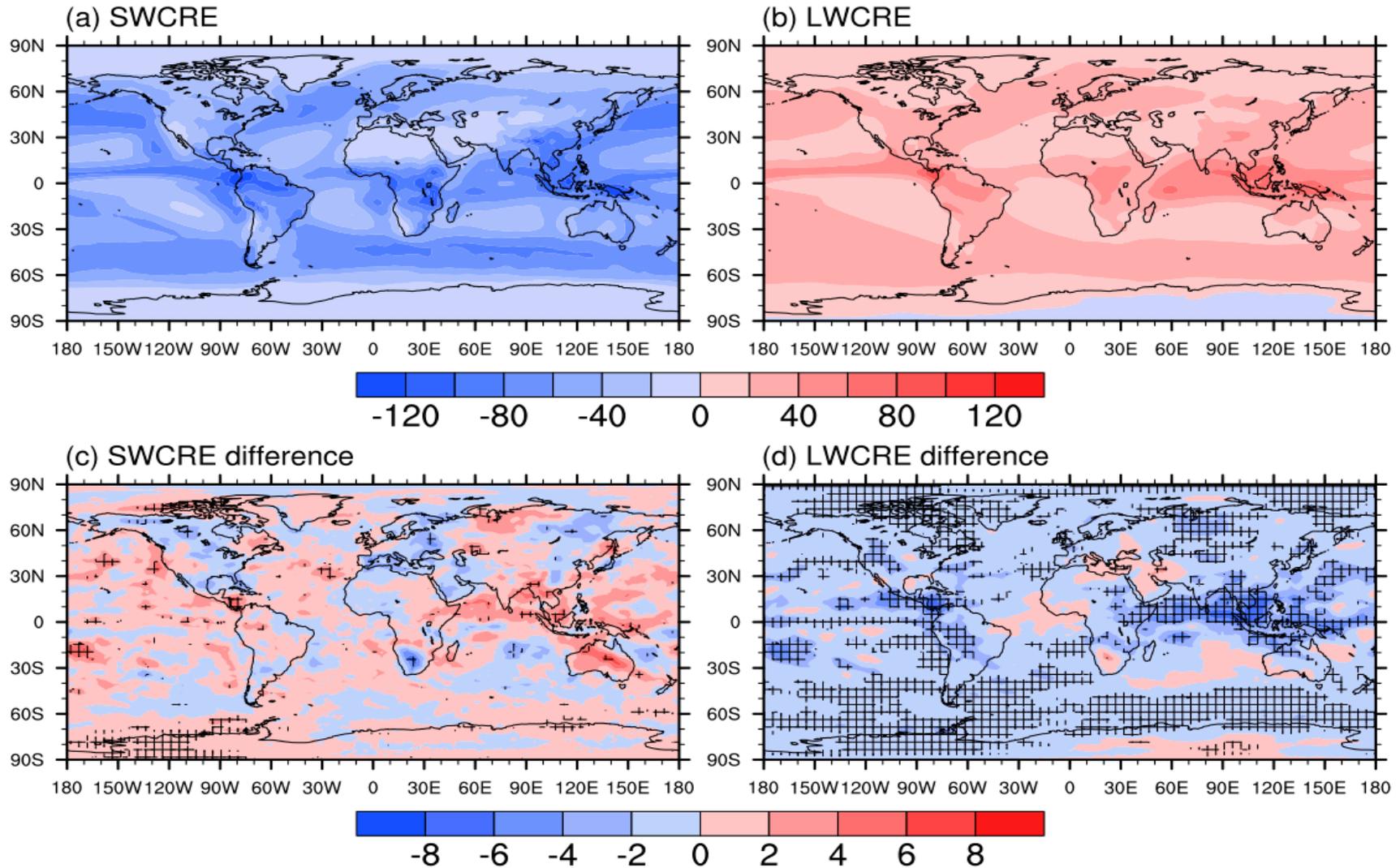
- IR Retrieval using the MODIS Bands 29 (8.5μm), 31 (11μm) and 32 (12μm);
- IR retrievals based on the CGOM computations overestimate the optical depth by 10% in comparison with the IIT+IGOM results;
- The retrieved effective particle sizes also show significant differences.



Differences in ice cloud radiative forcing simulated by RRTMG single-column RTM (CGOM case minus IIT+IGOM case)

- Standard mid-latitude summer atmospheric profiles
- Solar zenith angle at 60 degree
- Ice cloud layer at 12~13 km
- Larger difference in LW forcing
- SW forcing significant at small effective particle sizes

Ten-year mean annually averaged total cloud radiative forcing and the difference (CGOM-[IIT+IGOM]) from CAM5

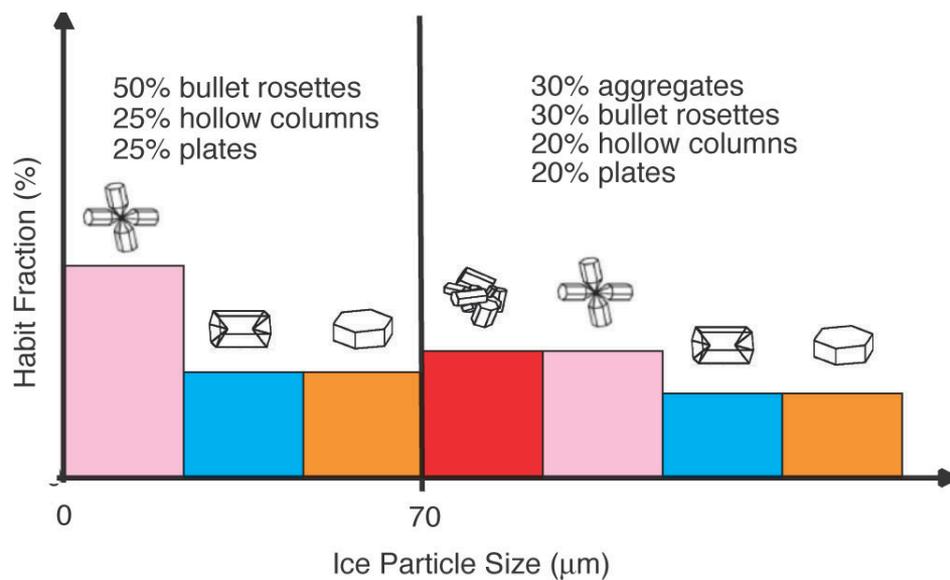


* Hatched regions are significant with 95% confidence level.

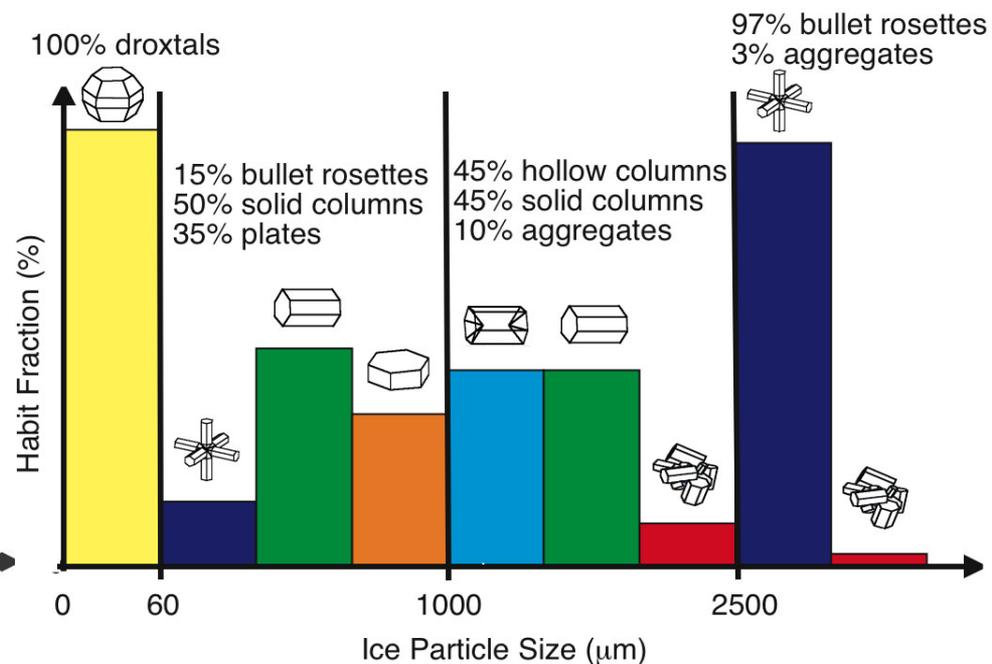
Two-Habit Model for Cirrus

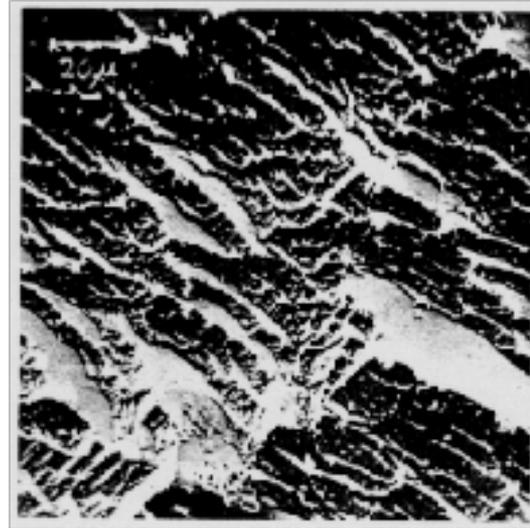
- **Microphysical properties:** A large database of median mass diameter and ice water content from in-situ measurements (courtesy of A. Heymsfield and K. Schmitt, NCAR)
- **Scattering properties from observations:** Featureless phase functions are frequently observed;
- **Scattering properties for climate modeling:** Relatively small asymmetry factors (approximately $g=0.75$ at visible) are required for GCM;
- **Spectral inconsistency for satellite retrievals:** Cloud optical depths retrieved from the VIS/NIR bands are larger than those from IR retrievals based on existing ice cloud models;
- **Polarization properties:** Polarized reflectance from the PARASOL

MODIS Collection 4

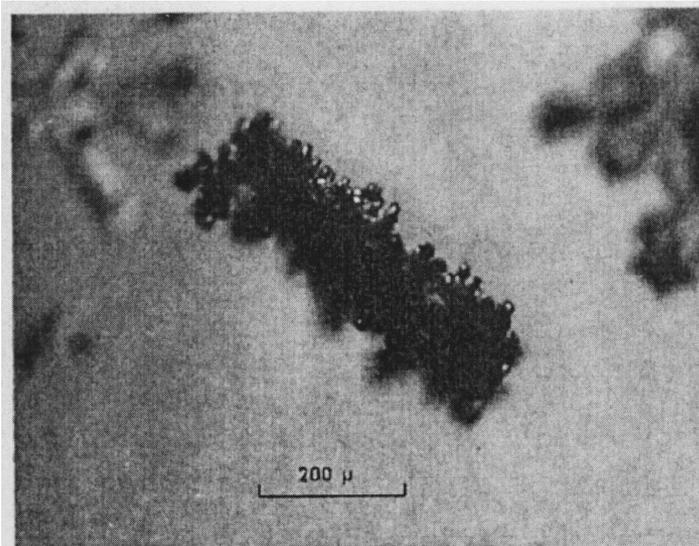


MODIS Collection 5



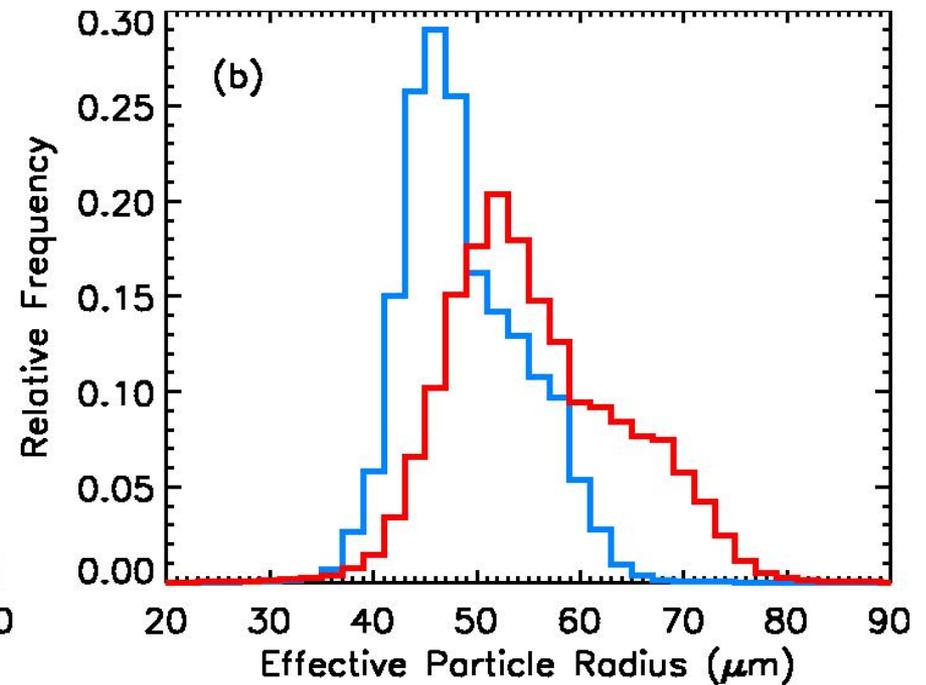
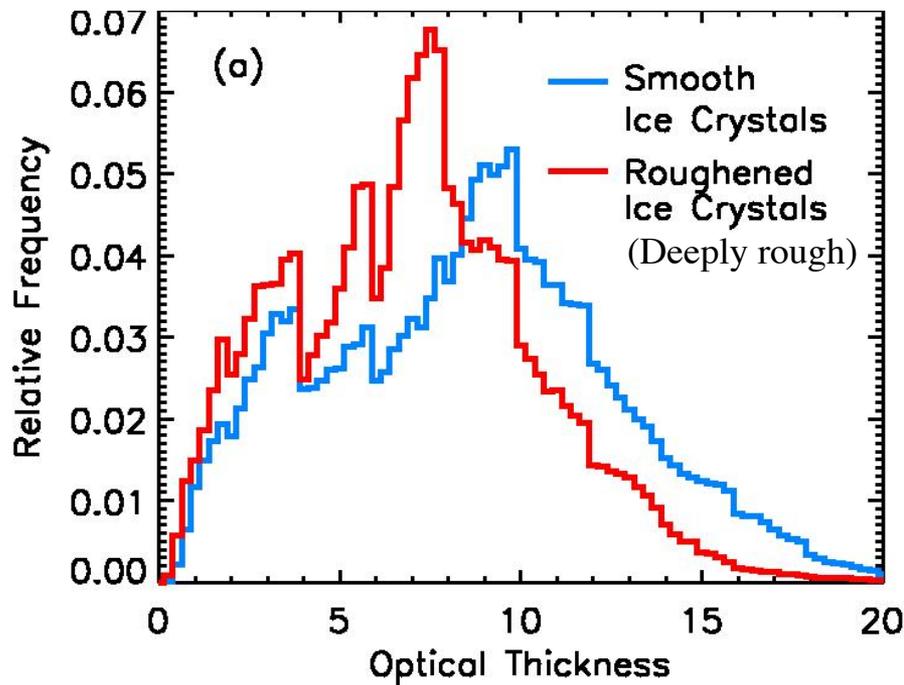


Surface roughness were observed for single crystals and polycrystalline ice by using an electronic microscope. Images adapted from Cross, 1968



The image of a rimed column ice crystal (adapted from Ono, 1969). The surface roughness of this ice crystal is evident.

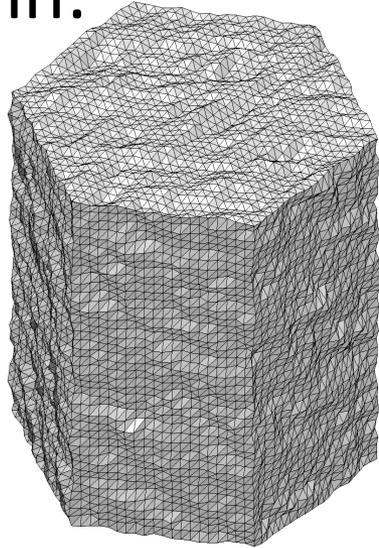
Effect of particle surface roughness on retrievals: Ice cloud optical thickness and effective particle size



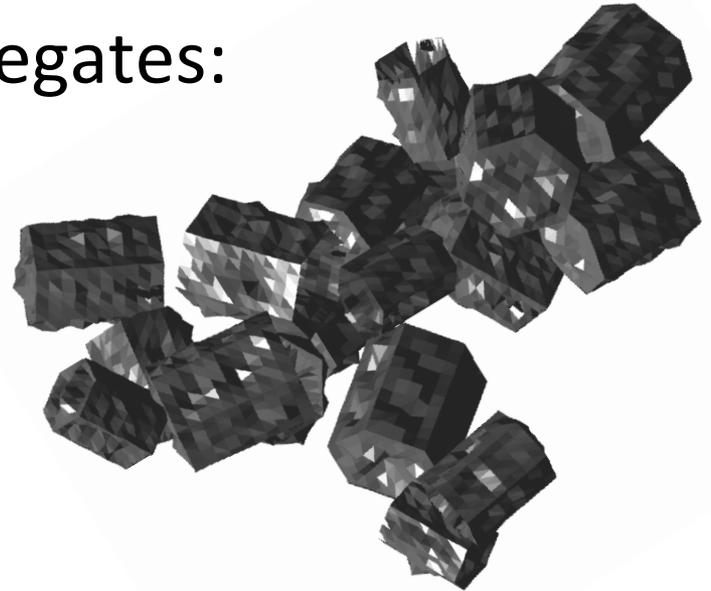
Two-Habit Model for Cirrus

Single Column:

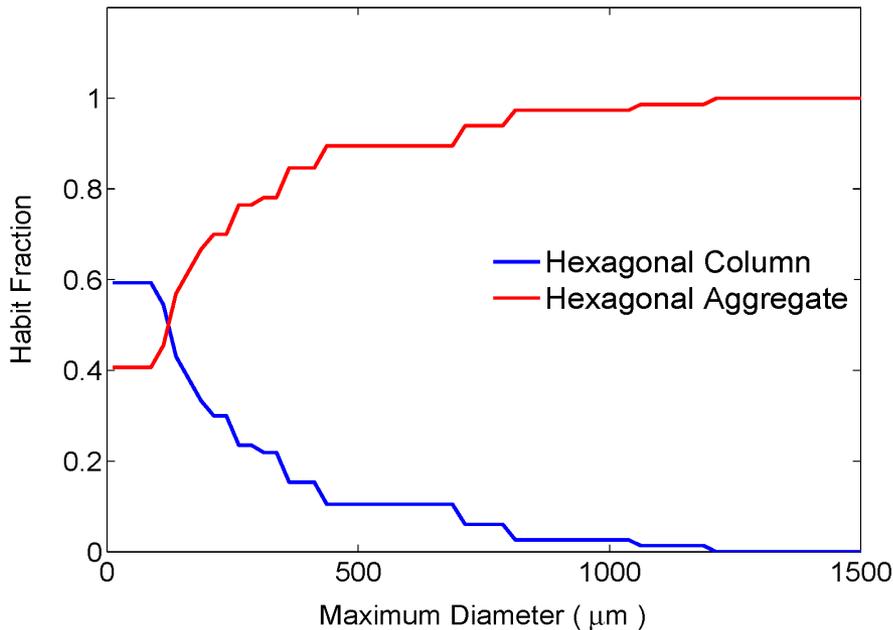
(Aspect ratio = 1)



Aggregates:



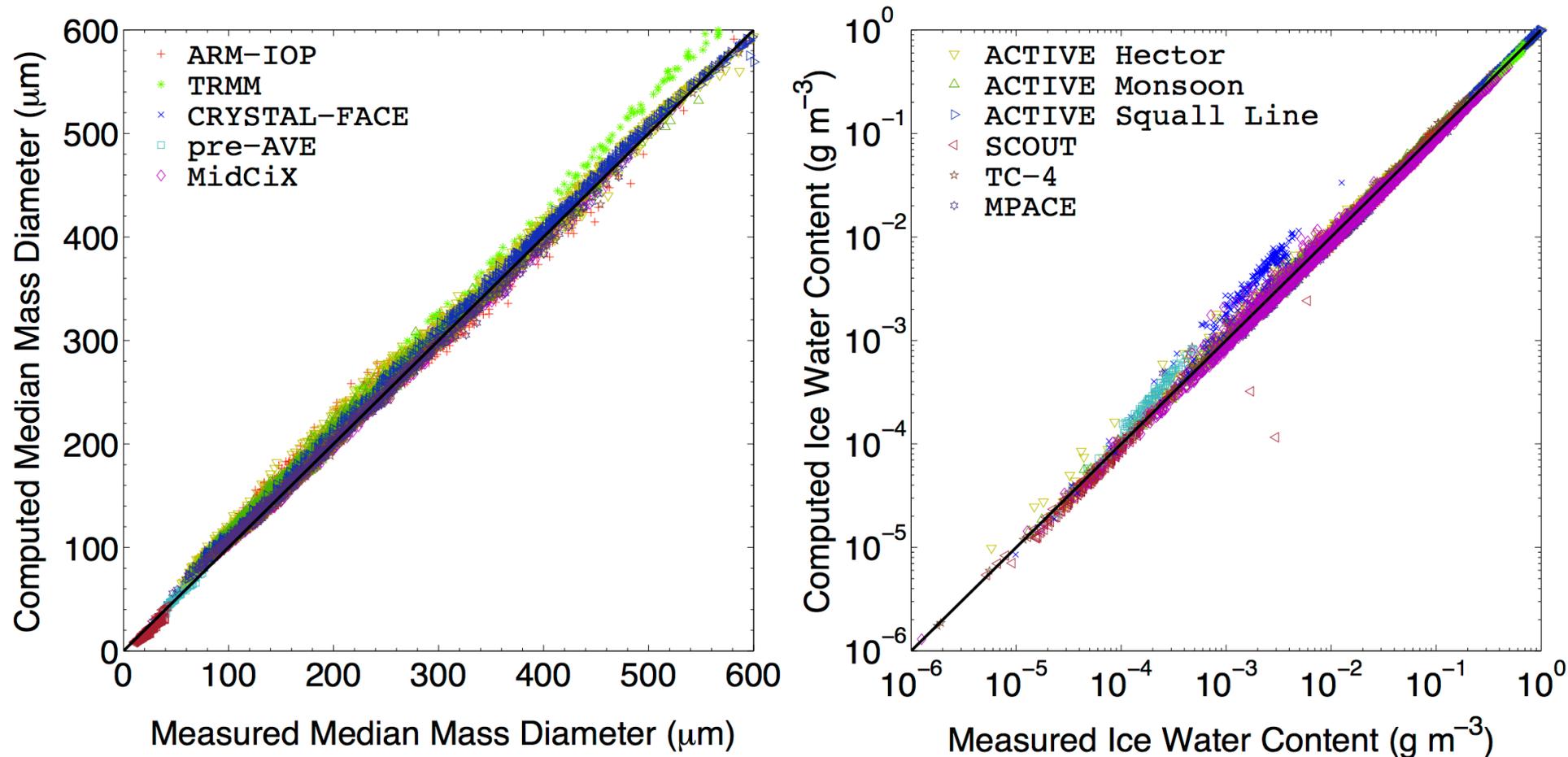
(20 hollow or solid columns)



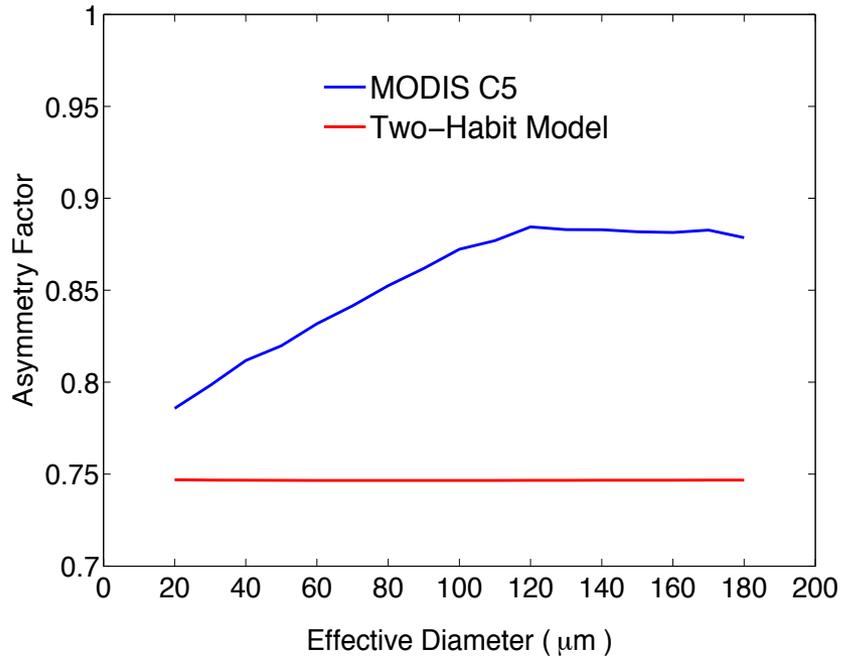
- The habit fractions of the two habit are determined by matching in-situ measured and computed microphysical properties
- More aggregates at large sizes

Microphysical Properties

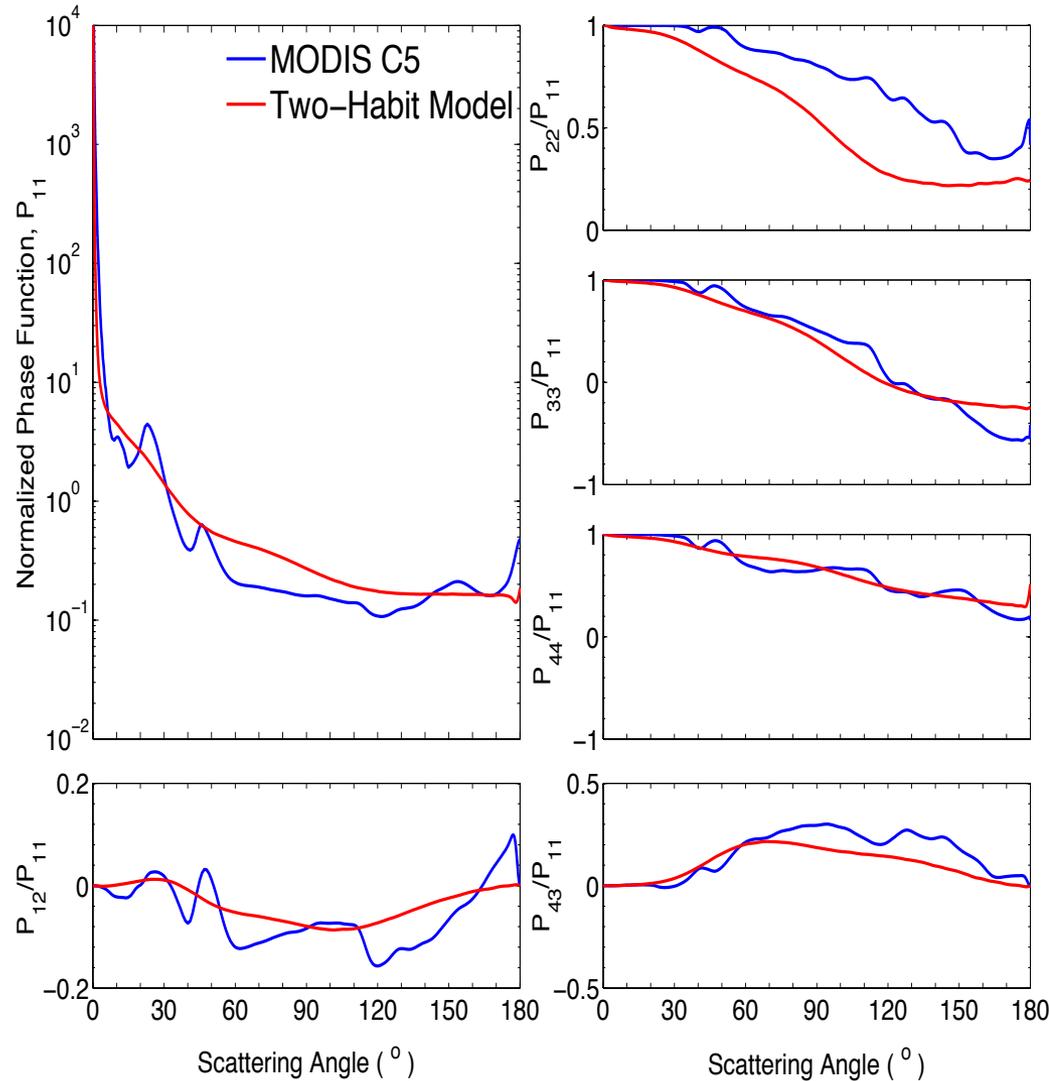
Comparison between in situ measurements and numerical model



Bulk scattering properties of the Two-Habit Model

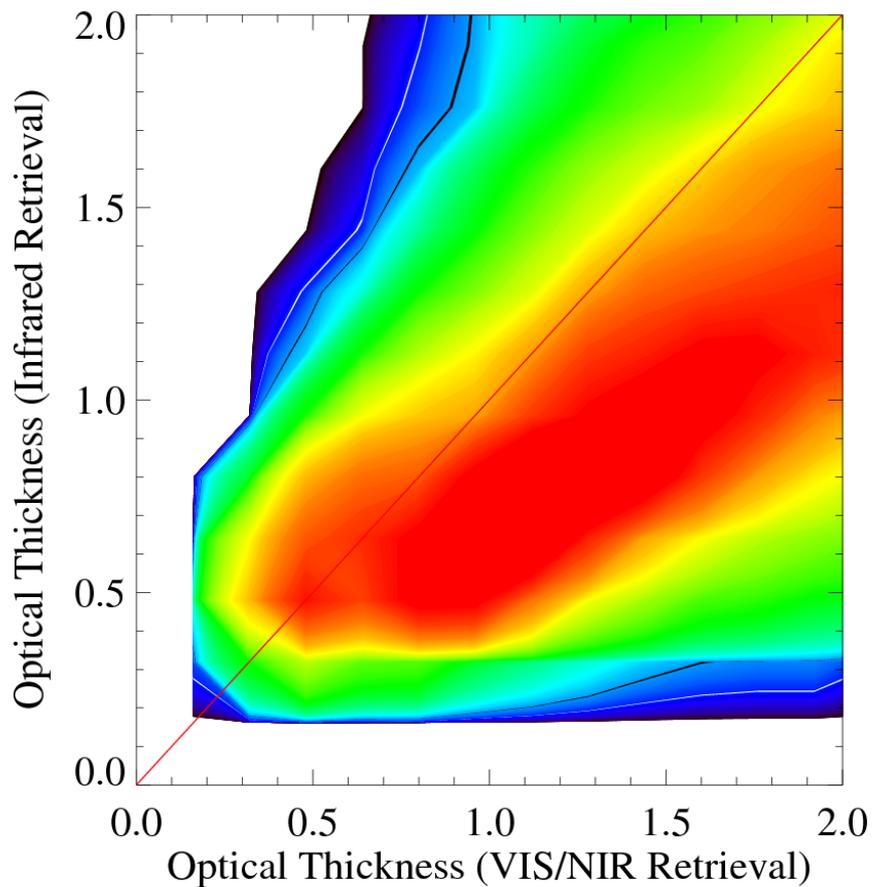


The asymmetry factor of the Two-Habit Model is approximately 0.75 at $\lambda=0.65 \mu\text{m}$

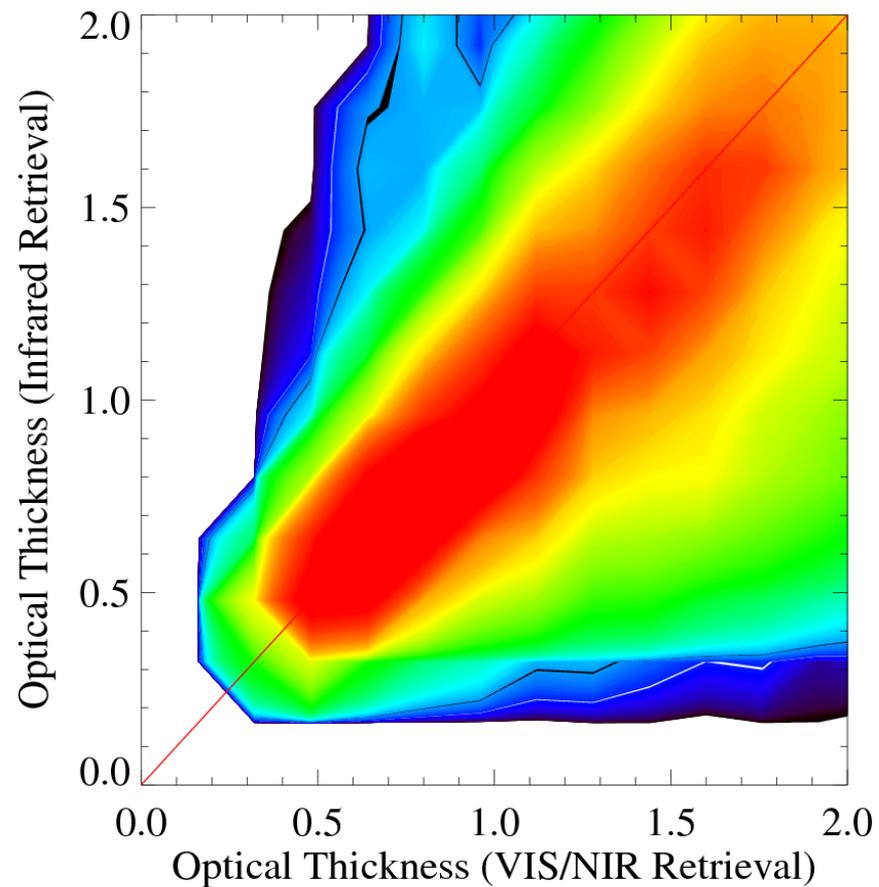


VIS/NIR and IR Retrievals

MODIS C5



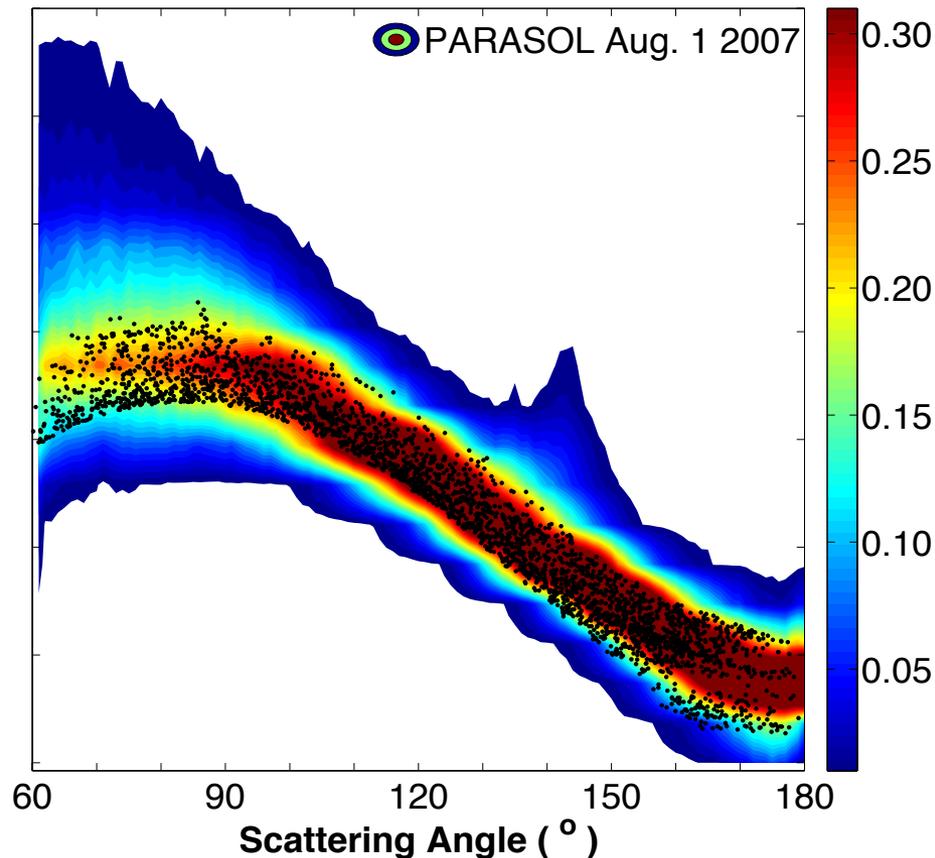
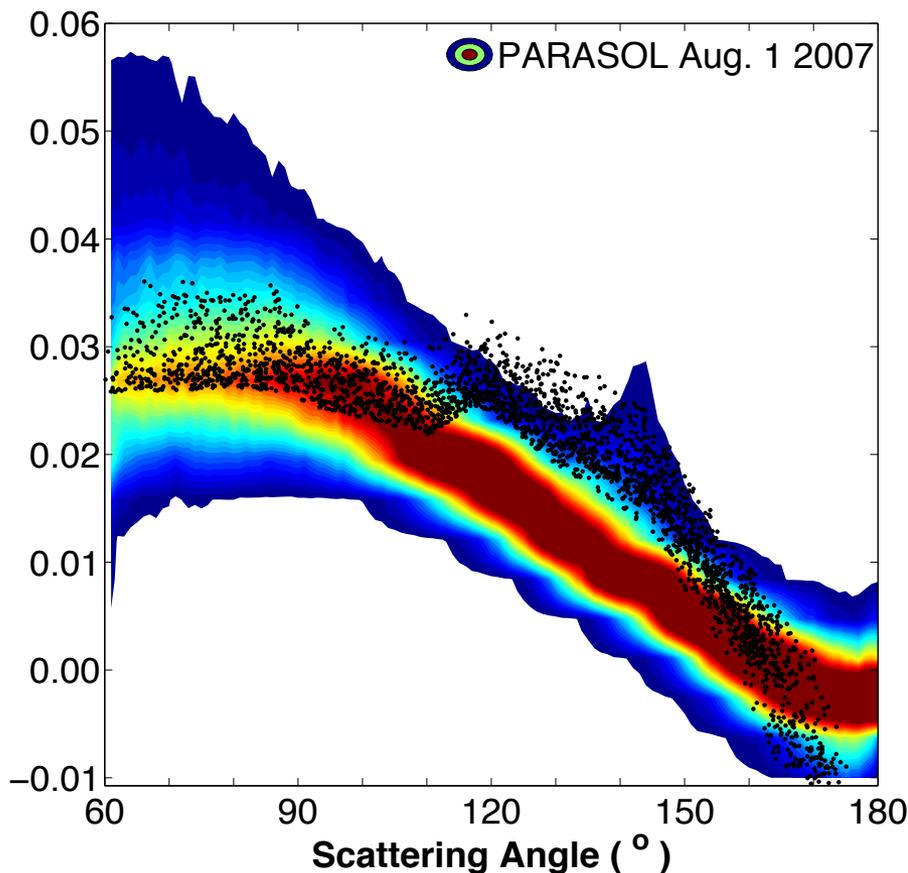
Two-Habit Model



Polarization properties of the Two-Habit Model

MODIS C5

Two-Habit Model



Conclusions

- A combination of the Invariant imbedding T-matrix and improved geometric optics methods significantly enhances the accuracy of the single-scattering simulations;
- The single-scattering properties based on the conventional geometric optics method (CGOM) is not sufficiently accurate for remote sensing, radiative transfer and climate studies;
- The Two-Habit Model and in-situ measurements are consistent in terms of ice cloud microphysical properties. Furthermore, the model provides spectrally consistent retrievals of cloud optical depth and also shows polarization properties that are consistent with that PARASOL observations.
- A new ice radiative property parameterization based on the two habit model is ongoing.